Elastic and Total Cross-Section Measurements by TOTEM: Past and Future

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CERN*

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Chania, Crete, Greece

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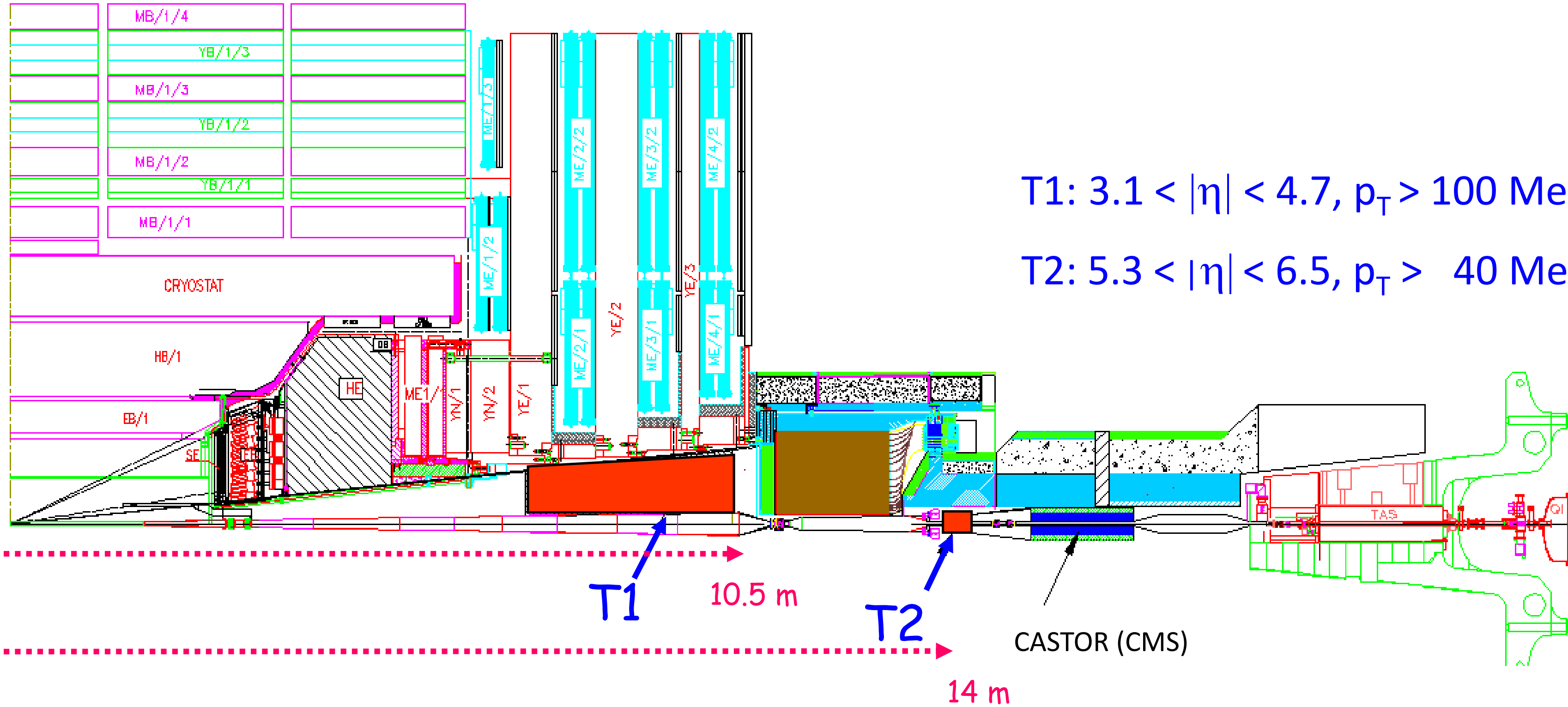
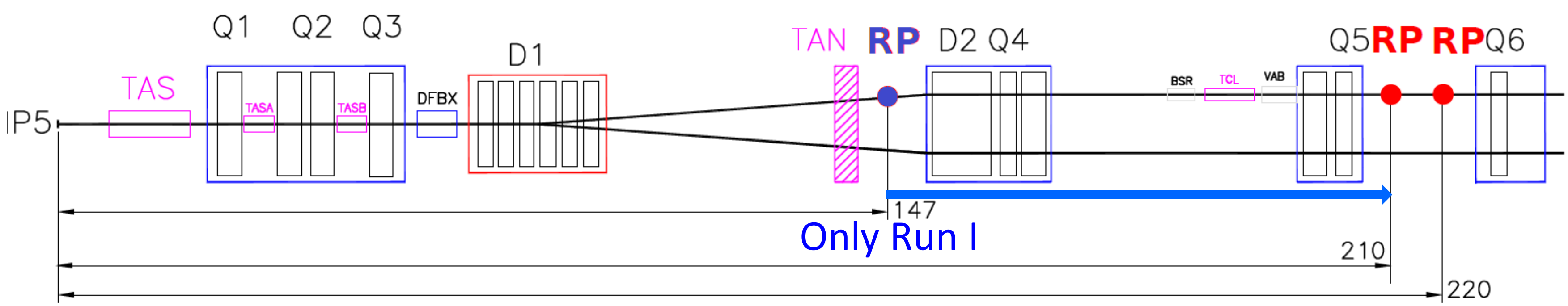
***Also at Wigner RCP, Budapest, Hungary**

Experimental layout of the TOTEM experiment (LHC Run II)



T1: 3.1 < |η| < 4.7, p_T > 100 MeV

T2: 5.3 < |η| < 6.5, p_T > 40 MeV

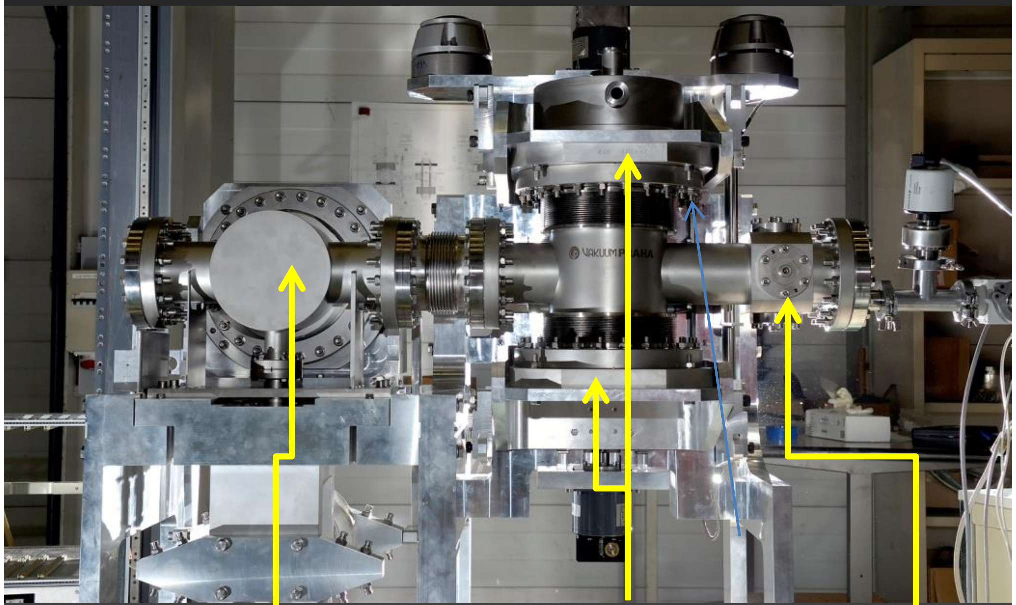


The Roman Pot (RP) stations of the TOTEM experiment

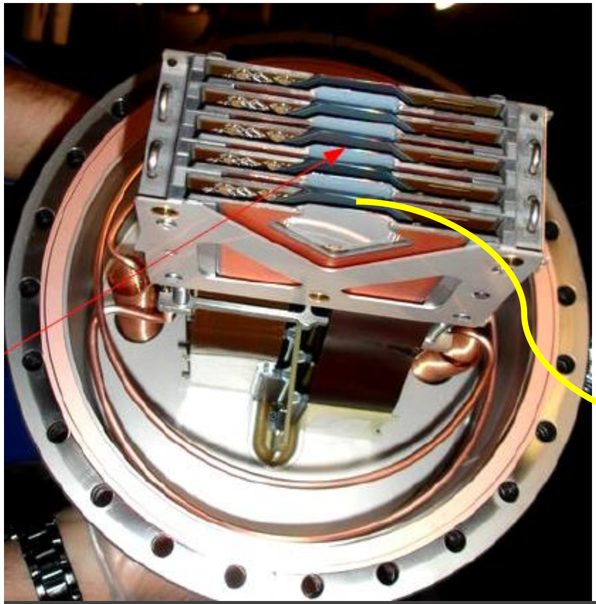
RP stations:

- 2 units (**N**ear, **F**ar) at about 5 m (RP220) and 10 m (RP210) distance
- Unit: 3 moveable RP to approach the beam and detect very small proton scattering angles (few μrad)
- BPM: precise position relative to beam
- Overlapping detectors: relative alignment (10 μm inside unit among 3 RPs)

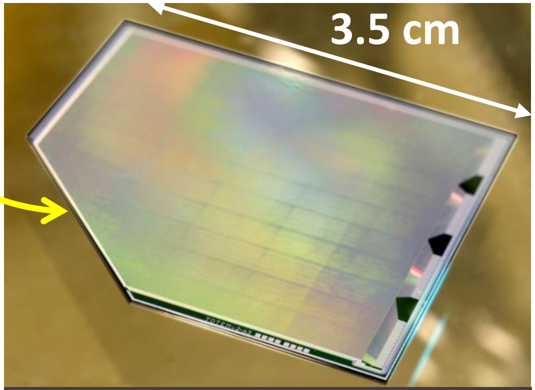
RP unit: 2 vertical, 1 horizontal pot + BPM



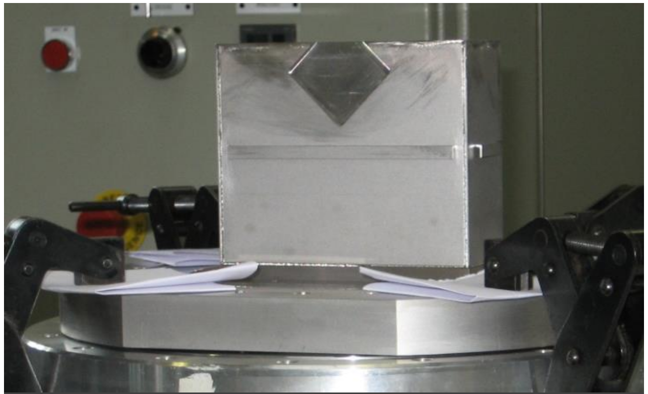
Horizontal RP Vertical RPs BPM



10 planes of edgeless detectors



Si edgeless detector



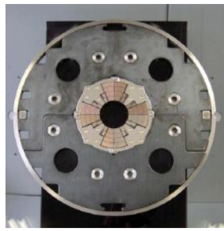
1 Roman Pot

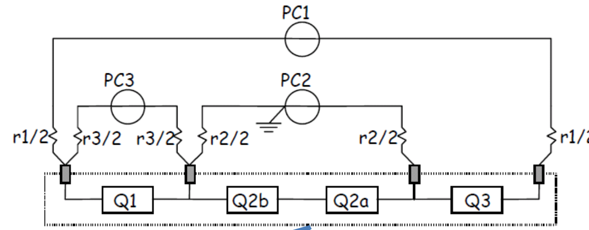
LHC optics at IP5 briefly

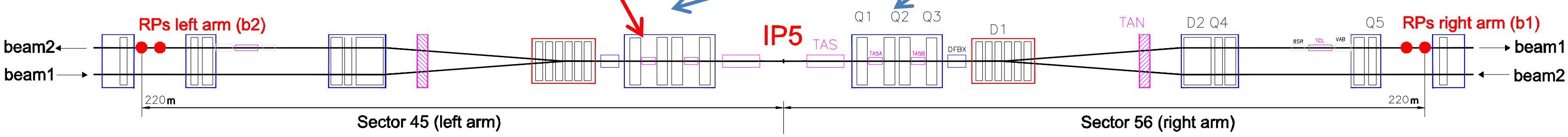
Sketch of the LHC magnet lattice at IP5:

MQXA quadrupole

$$k = \frac{1}{B\rho}\frac{dB_z}{dx}$$







s: distance from IP5 (*≡IP5)

Measured

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \xi \end{pmatrix}_{RP} = \begin{pmatrix} v_x & L_x & m_{13} & m_{14} & D_x \\ v'_x & L'_x & m_{23} & m_{24} & D'_x \\ m_{31} & m_{32} & v_y & L_y & D_y \\ m_{41} & m_{42} & v'_y & L'_y & D'_y \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x^* \\ \Theta^*_x \\ y^* \\ \Theta^*_y \\ \xi^* \end{pmatrix}$$

$$\boxed{\sigma(\Theta) = \sqrt{\varepsilon / \beta_x(s)}}$$

Determines angular resolution.

Introduction

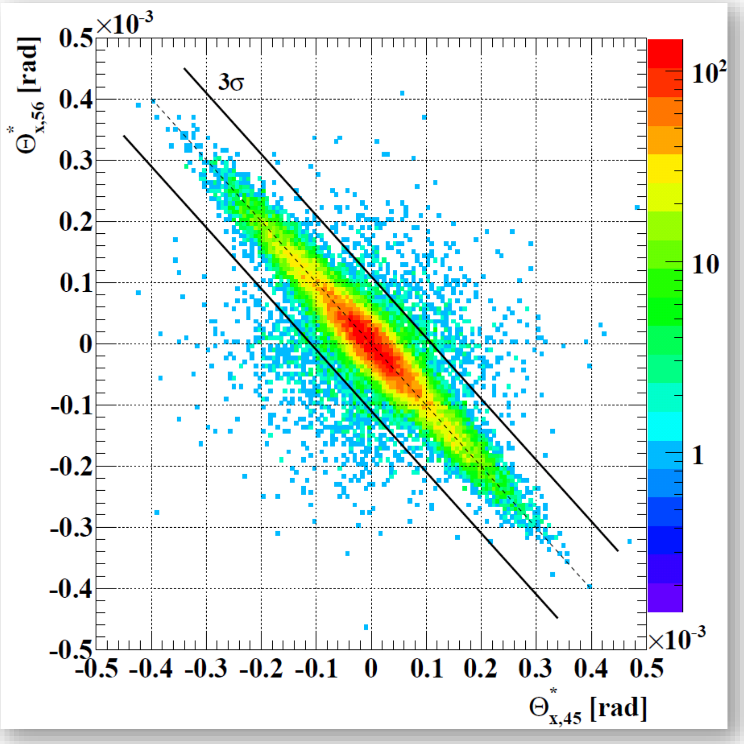
List of TOTEM publications

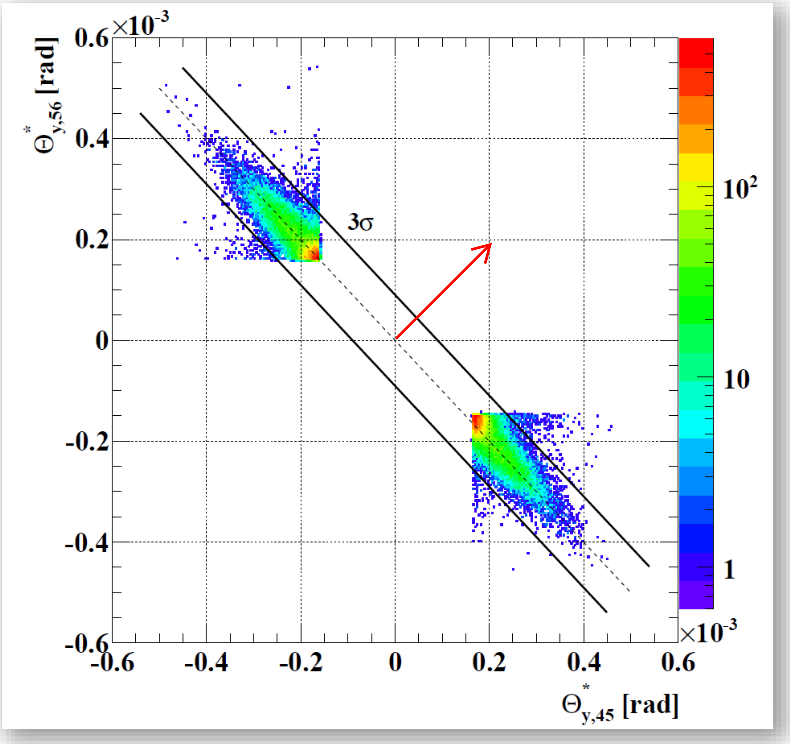
http://totem.web.cern.ch/Totem/publ_new.html

Reconstructed proton kinematics with β* = 3.5 m optics

Momentum conservation is required in elastic events:

- Published in EPL **95** (2011) 41001

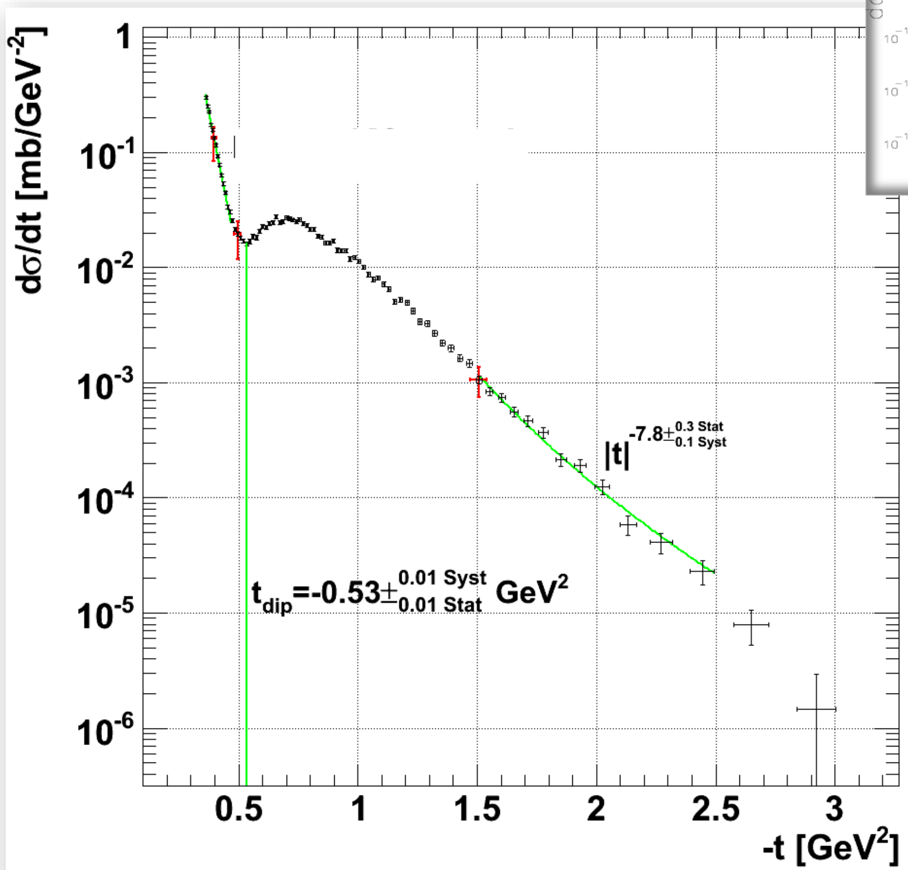


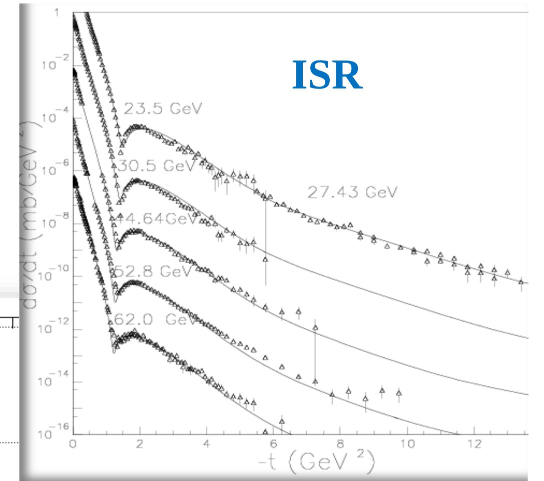


The elastic $d\sigma/dt$ distribution at $\sqrt{s}$ = 7 TeV (β^* = 3.5 m)

Published in EPL **95** (2011) 41001:

- $|t|$ range spans from 0.36 to 2.5 GeV^2
- Below $|t|$ = 0.47 GeV^2 exponential $e^{-B|t|}$ behavior
- Dip moves to lower $|t|$, proton becomes "larger"
- 1.5 - 2.5 GeV^2 power low behavior $|t|^{-n}$

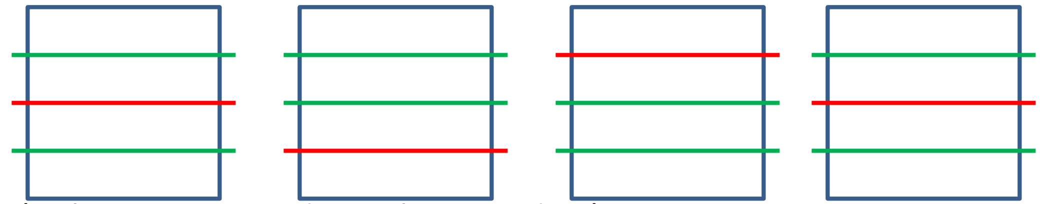




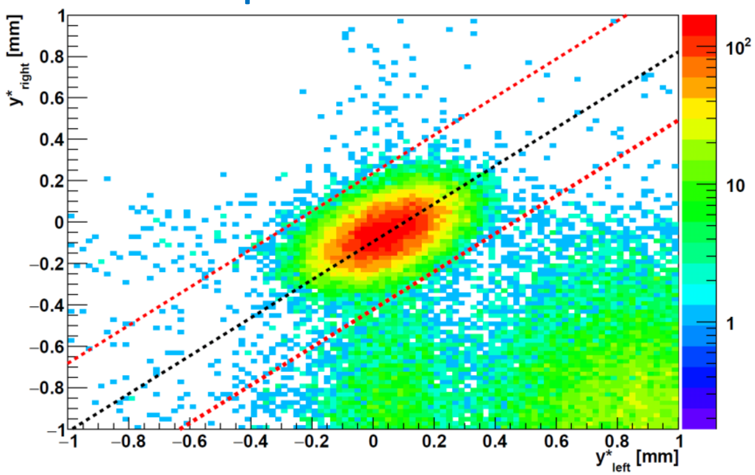
TOTEM elastic scattering measurement at $\sqrt{s}$ = 2.76 TeV

Strong background: elastic candidate selection from multitracks

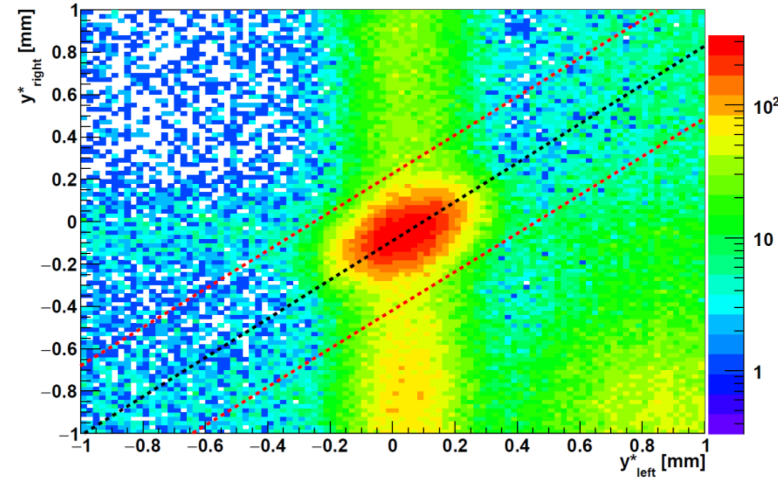
- RP can resolve uniquely single tracks
- Otherwise: multitrack candidate array / RP
- Elastic cuts defined with unique tracks
- **Every** combination of the 4 RPs of a diagonal
- **One** combination is selected with elastic cuts (+physics oriented topology studies)



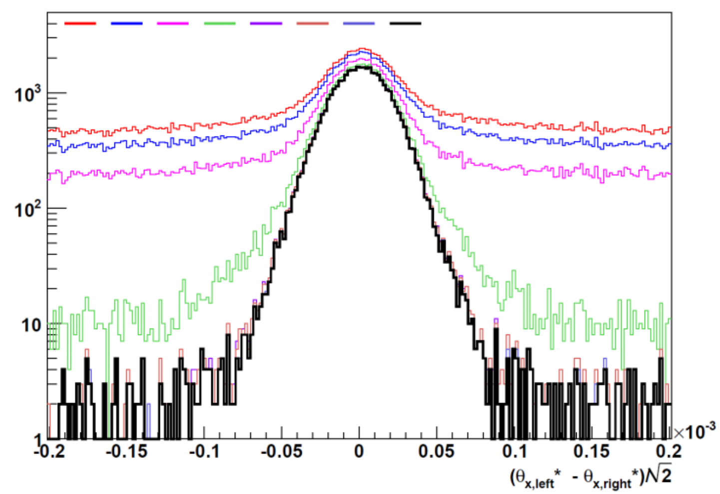
Unique tracks to define cuts



… to select elastic candidates from multitracks



- Progressive selection of elastic candidates / cut

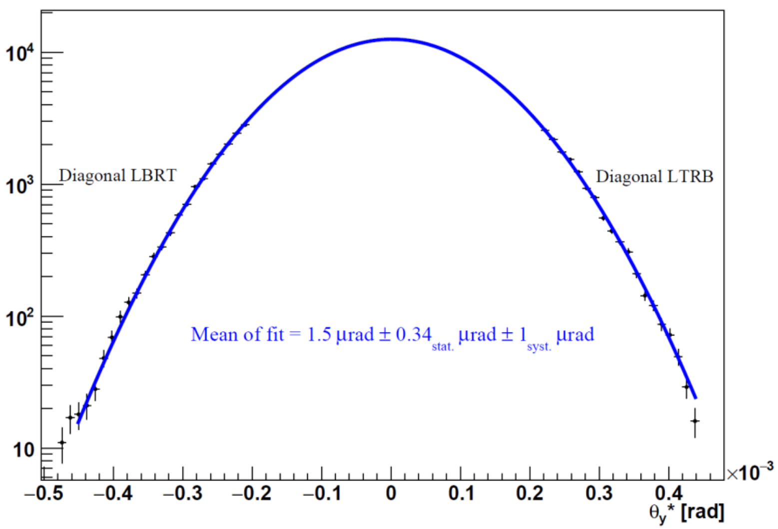


RP alignment and LHC optics calibration

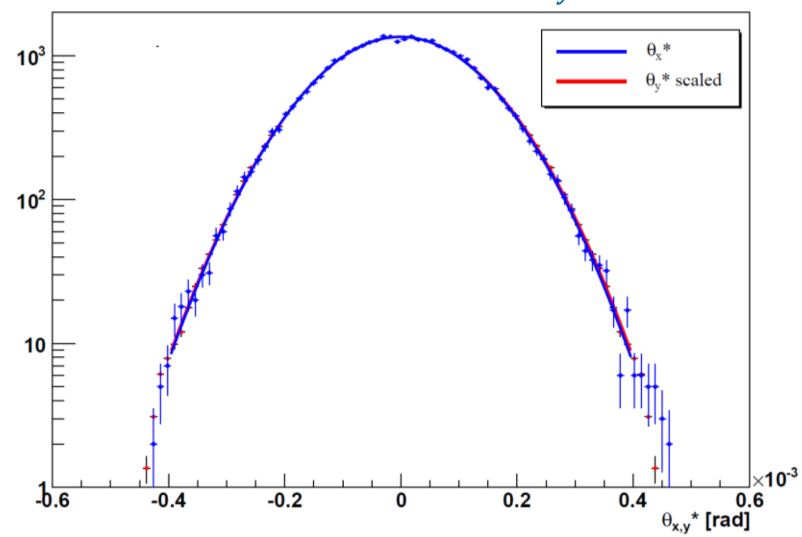
Horizontal RPs were not inserted:

- No track based **top - bottom** RP alignment
- Horizontal and relative near-far alignment is done
- New methods to find absolute y-alignment of the 2 diagonals
- 2 diagonals: 2 constraints from elastic scattering symmetries

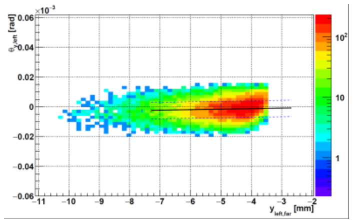
1st constraint: alignment of θ_y^* barycenter to 0



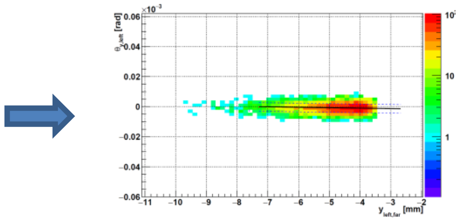
2nd constraint: alignment of θ_y^* to θ_x^*



- Optics calibration done in the usual way (alignment independent procedure)
- Careful measurement of optics estimators:



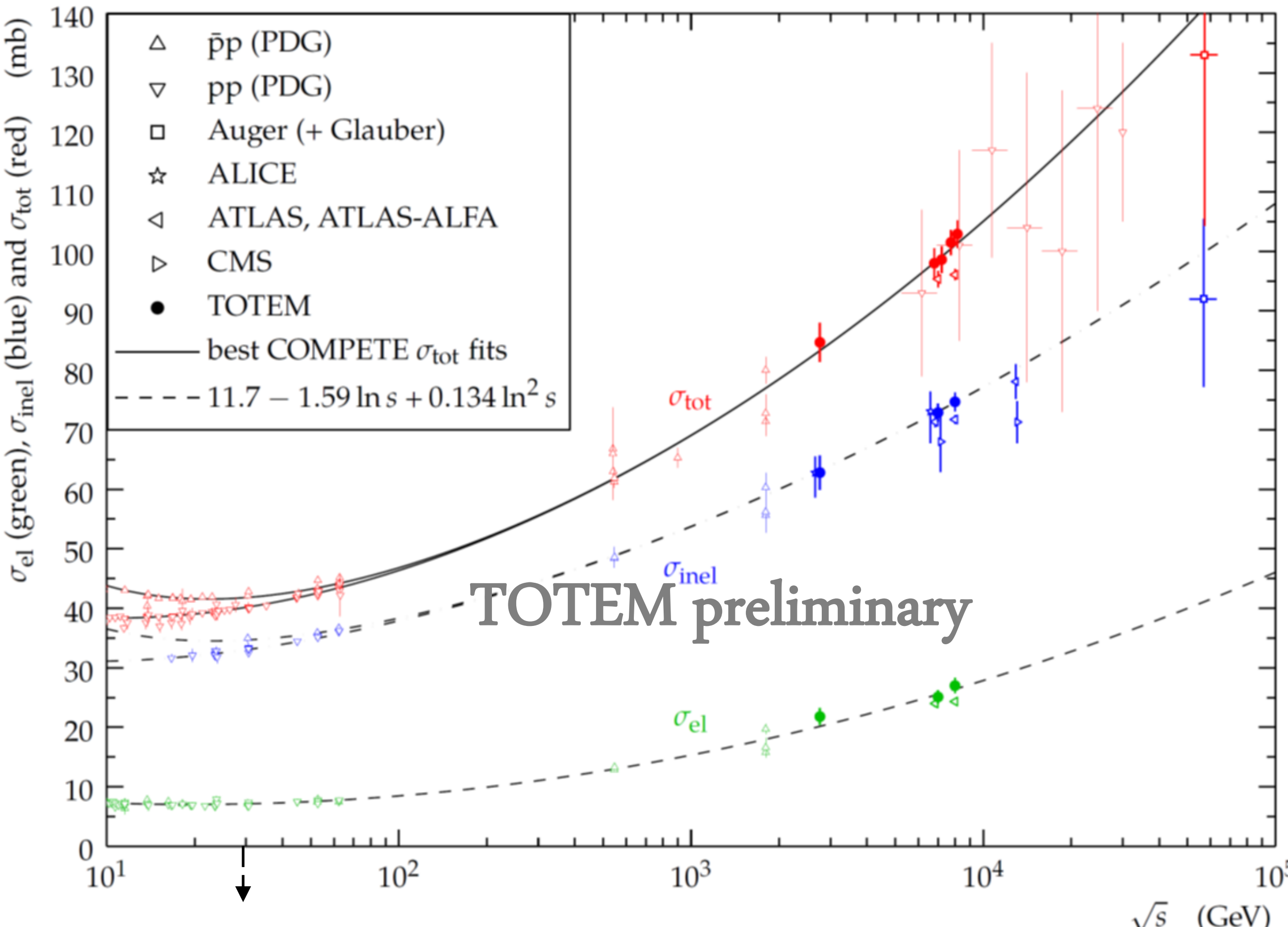
After y* vertex cut



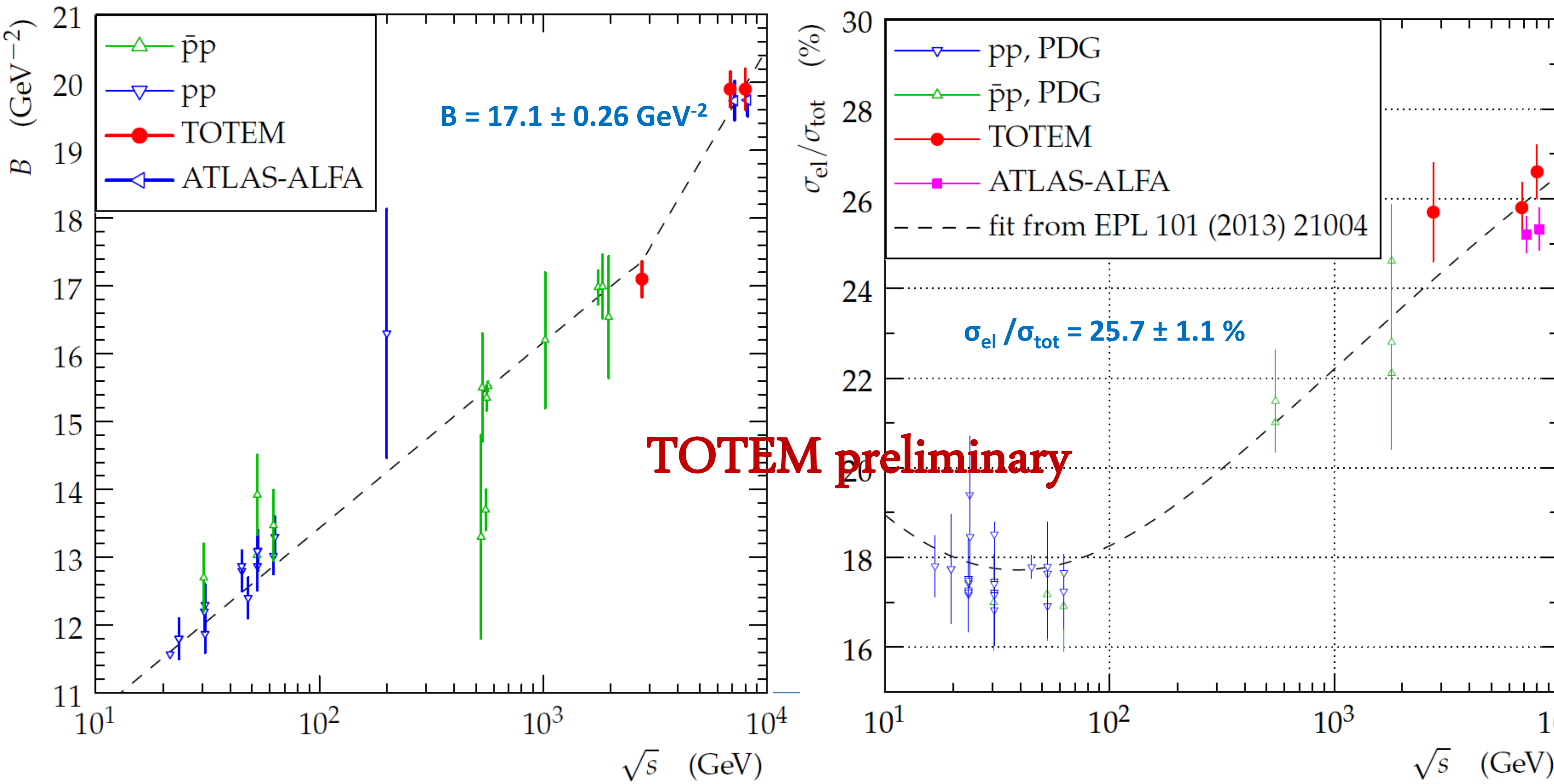
2.76 TeV luminosity independent cross-sections (β* = 11 m optics)

$$\sigma_{\rm tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2}\cdot\frac{\left.\frac{dN_{\rm el}}{dt}\right|_{t=0}}{N_{\rm el}+N_{\rm inel}} \qquad \rho = \left.\frac{\mathrm{Re}\,A^H}{\mathrm{Im}\,A^H}\right|_{t=0}$$

σ_{tot} [mb]	σ_{el} [mb]	σ_{inel} [mb]
84.7 ± 3.3	21.8 ± 1.4	62.8 ± 2.9



The nuclear slope B and the σ_{el}/σ_{tot} ratio at $\sqrt{s}$ = 2.76 TeV



TOTEM cross-section measurement at $\sqrt{s}$ = 13 TeV

β^* = 90 m, $5\sigma_{RP}$ RP distance

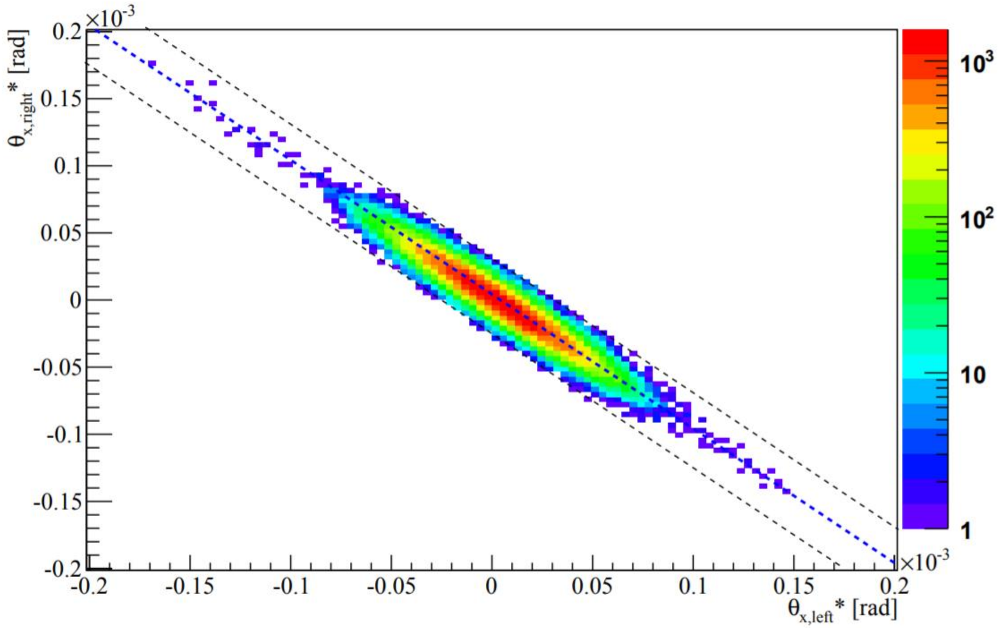
Kinematics, cuts and signal selection at 13 TeV

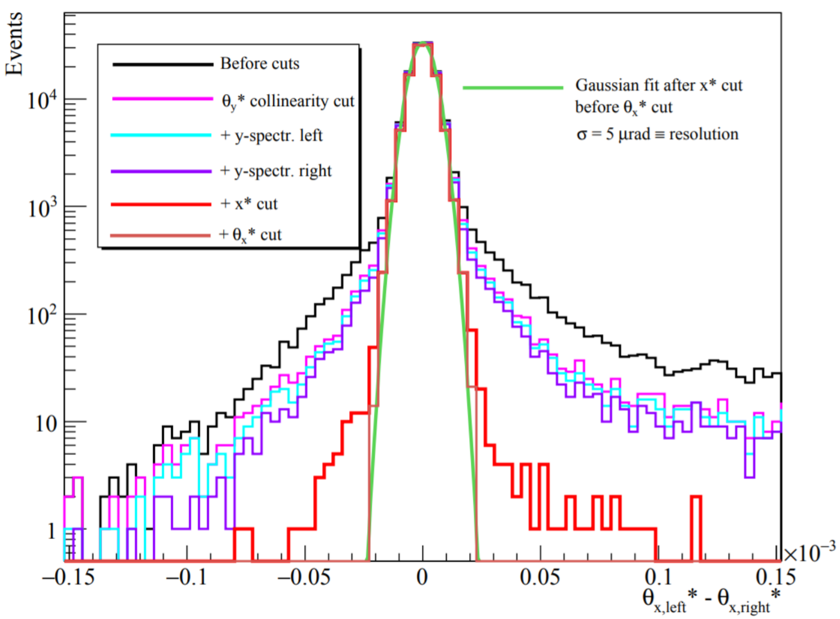
Note:

- Reconstruction of kinematics:

$$\theta_x^* = \frac{1}{\frac{dL_x}{ds}}\left(\theta_x - \frac{dv_x}{ds}x^*\right), \theta_y^* = \frac{y}{L_y}$$

- Clean sample after usual elastic cuts
- Optics matching → kinematics reconstruction uncertainty ~ 2 permil





Inefficiencies and corresponding physics corrections

Note:

- Large O(20 %) but well measurable, inefficiencies:

Correction [%]	DS1		DS2	
	Diag. 1	Diag. 2	Diag. 1	Diag. 2
$\mathcal{I}_{3/4}$	25.86 ± 0.2	22.04 ± 0.2	20.34 ± 0.1	21.37 ± 0.1
$\mathcal{I}_{2/4}$	19.91 ± 0.2	16.16 ± 0.2	16.09 ± 0.2	17.11 ± 0.2
$\mathcal{I}_{2/4\,\mathrm{diff.}}$	2.38 ± 0.05	1.61 ± 0.04	1.33 ± 0.02	1.5 ± 0.02
η_{d}	80.93 ± 0.01		99.95 ± 0.01	
η_{tr}	99.9 ± 0.1		99.9 ± 0.1	

- Total correction per event:

$$f(\theta^*, \theta_y^*) = \frac{1}{\eta_{\mathrm{d}}\eta_{\mathrm{tr}}} \cdot \frac{\mathcal{C}(\theta^*, \theta_y^*)}{1 - \mathcal{I}} \cdot \frac{1}{\Delta t}$$

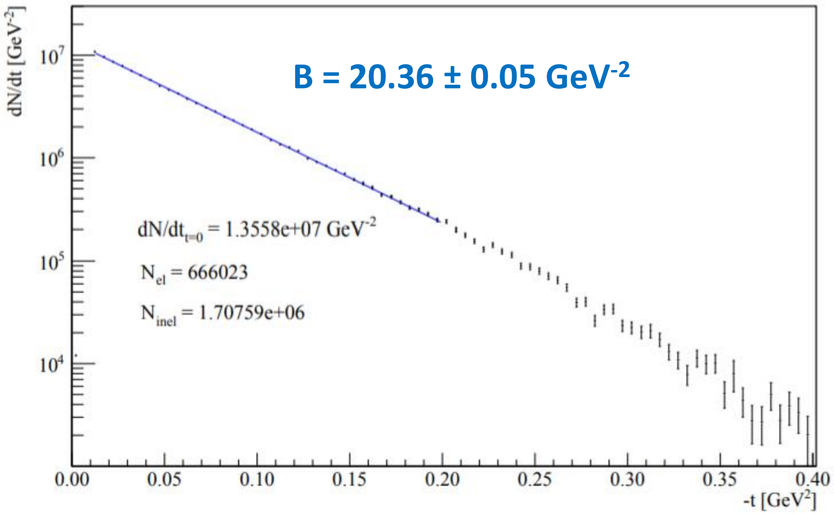
$$\mathcal{I} = \mathcal{I}_{3/4}(\theta_y^*) + \mathcal{I}_{2/4} + \mathcal{I}_{2/4\,\mathrm{diff}}$$

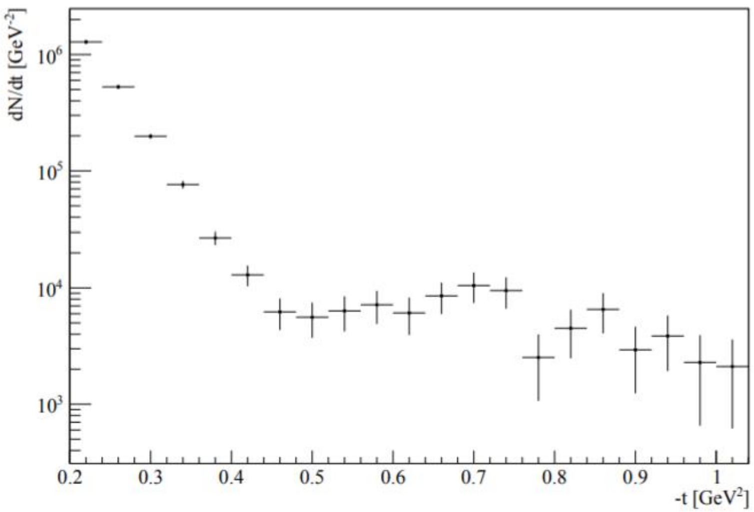
Main observables at 13 TeV

Note:

- $N_{inel,obs}$ is measured with the T2 inelastic telescope

Data set	Unit	DS1	DS2
$N_{\mathrm{el,obs}}$		105729	216825
$N_{\mathrm{inel,obs}}$		773000	1488343
N_{el}		$4.273 \cdot 10^5 \pm 0.5\ \% \pm 2.3\ \%$	$6.660 \cdot 10^5 \pm 0.5\ \% \pm 2.3\ \%$
$\mathrm{d}N_{\mathrm{el}}/\mathrm{d}t\|_{t=0}$	$[\mathrm{GeV}^{-2}]$	$8.674 \cdot 10^6 \pm 0.4\ \% \pm 1.6\ \%$	$1.356 \cdot 10^7 \pm 0.4\ \% \pm 1.6\ \%$
N_{inel}		$1.097 \cdot 10^6 \pm 0.1\ \% \pm 3.7\ \%$	$1.708 \cdot 10^6 \pm 0.1\ \% \pm 3.7\ \%$





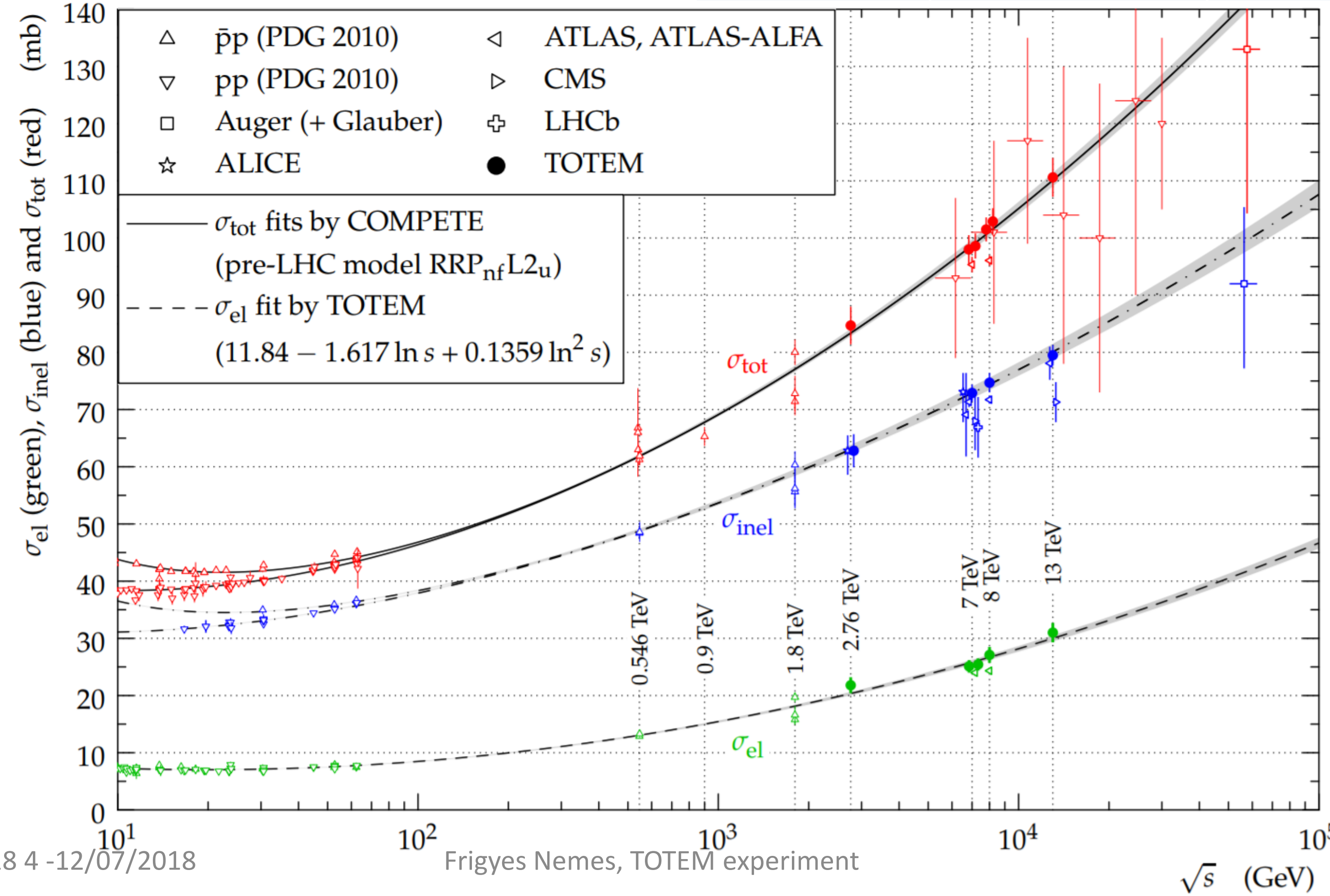
Cross sections at 13 TeV & summary plot

Provides normalization at 13 TeV to:

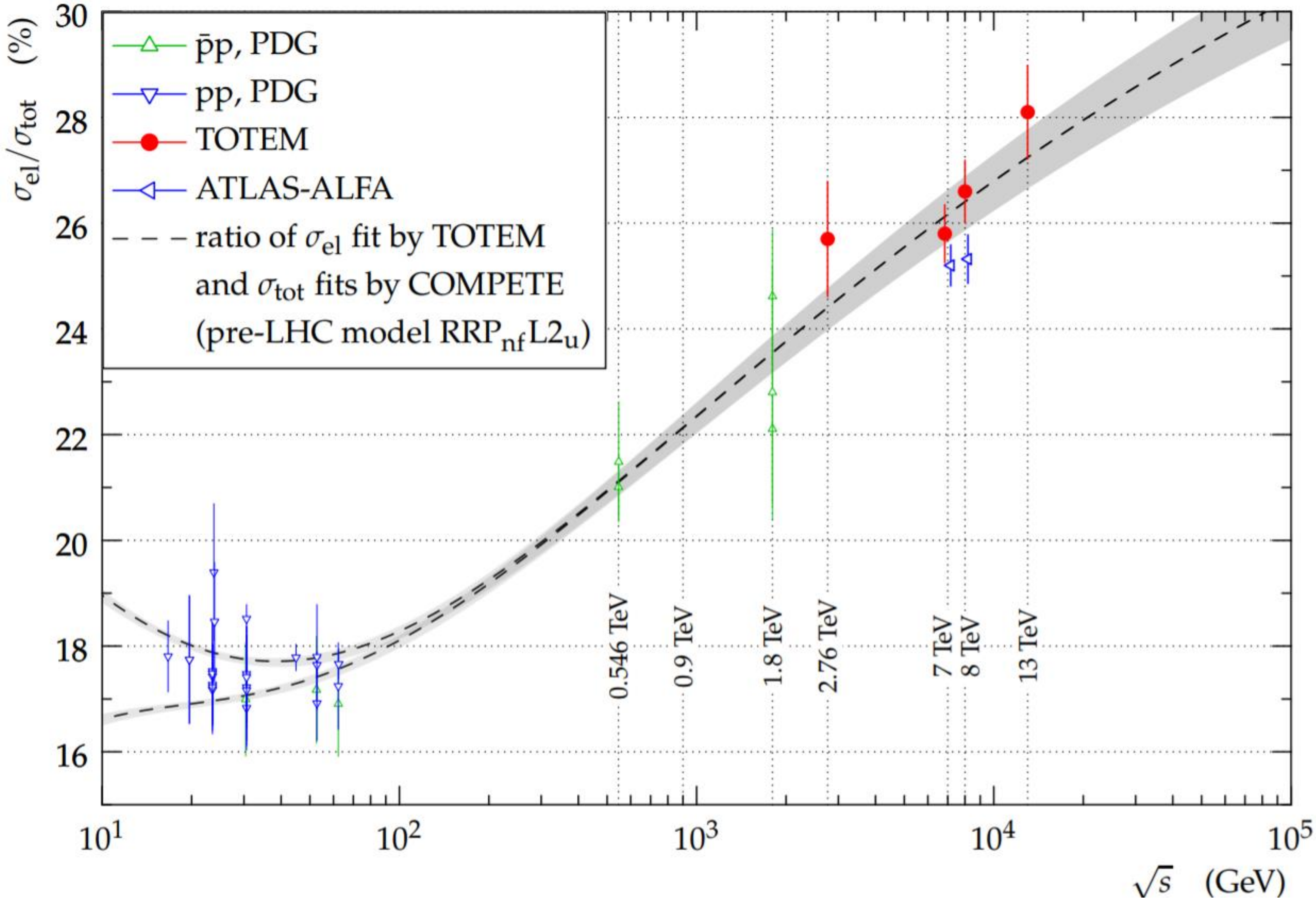
- β* = 2500 m
- β* = 90 m, 10 σ RP distance

ρ = 0.1

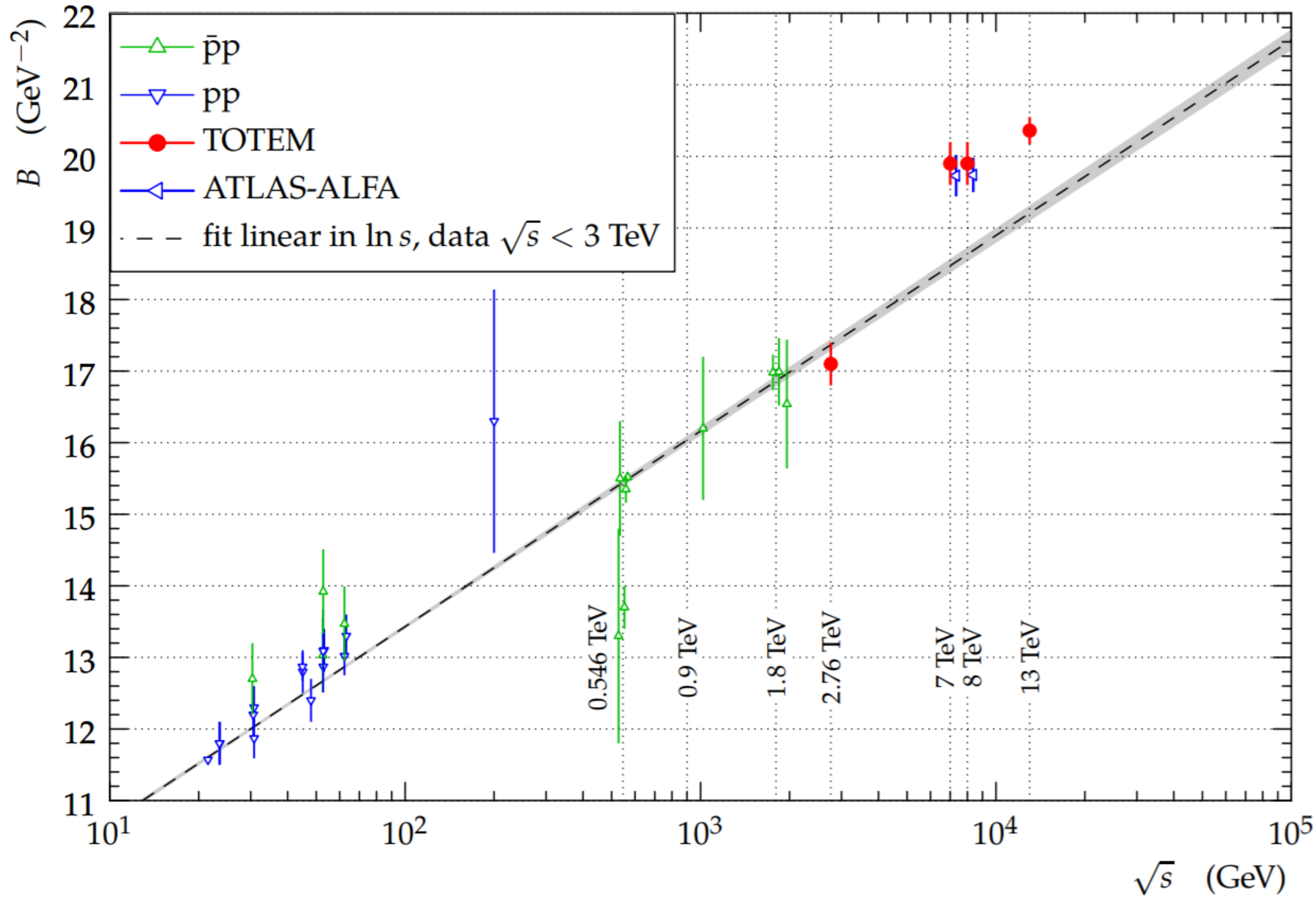
σ_{tot} [mb]	σ_{el} [mb]	σ_{inel} [mb]
110.6 ± 3.4	31.0 ± 1.7	79.5 ± 1.8



The σ_{el}/σ_{tot} ratio



Overview of the nuclear slope B evolution with energy



ρ measurement at √s = 13 TeV

Probing the existence of colourless three-gluon bound state

β* = 2500 m

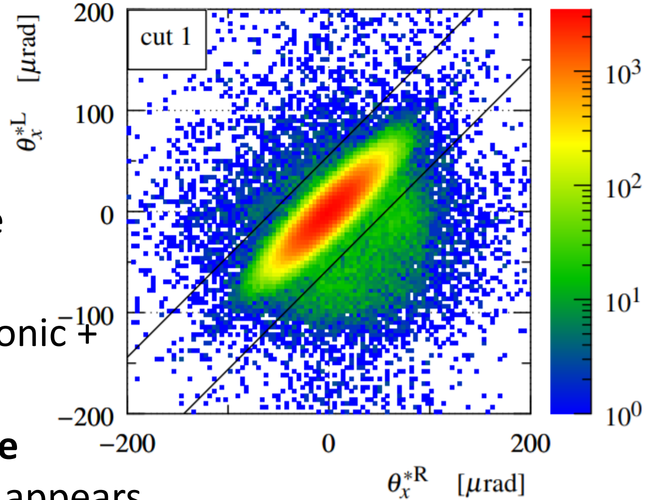
Coulomb-nuclear interference the ρ quantity

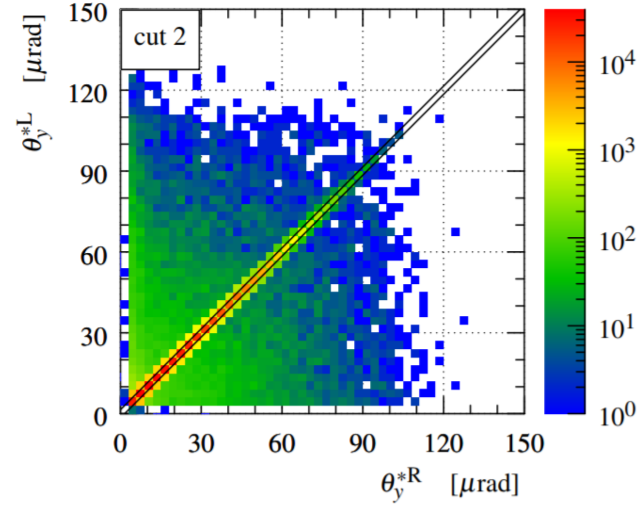
Basic properties of the data:

- $|t|_{min}$ = 8×10^{-4} GeV^2

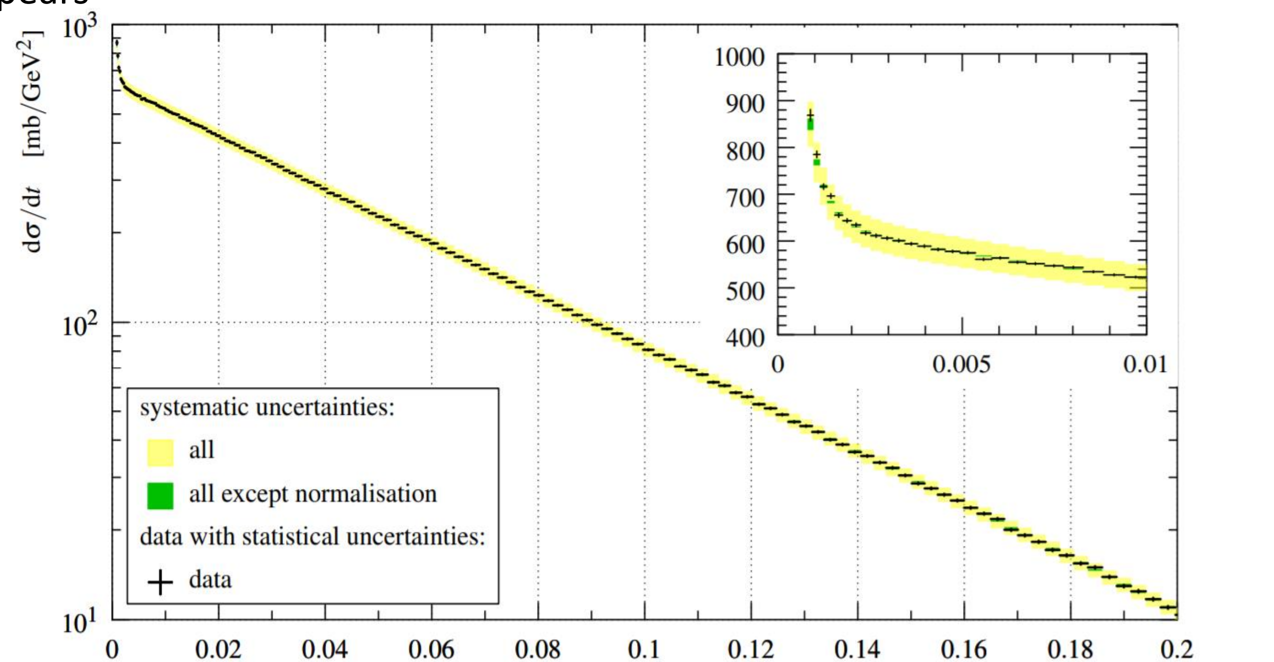
Analysis aims:

- Measure $d\sigma_{el}/dt$ at the smallest possible $|t|$
- A_{C+H}= Coulomb + Hadronic + Interference terms
- Interference: the **phase** of hadronic amplitude appears





$$\frac{d\sigma}{dt} \propto \left|A_{C+H}\right|^2$$

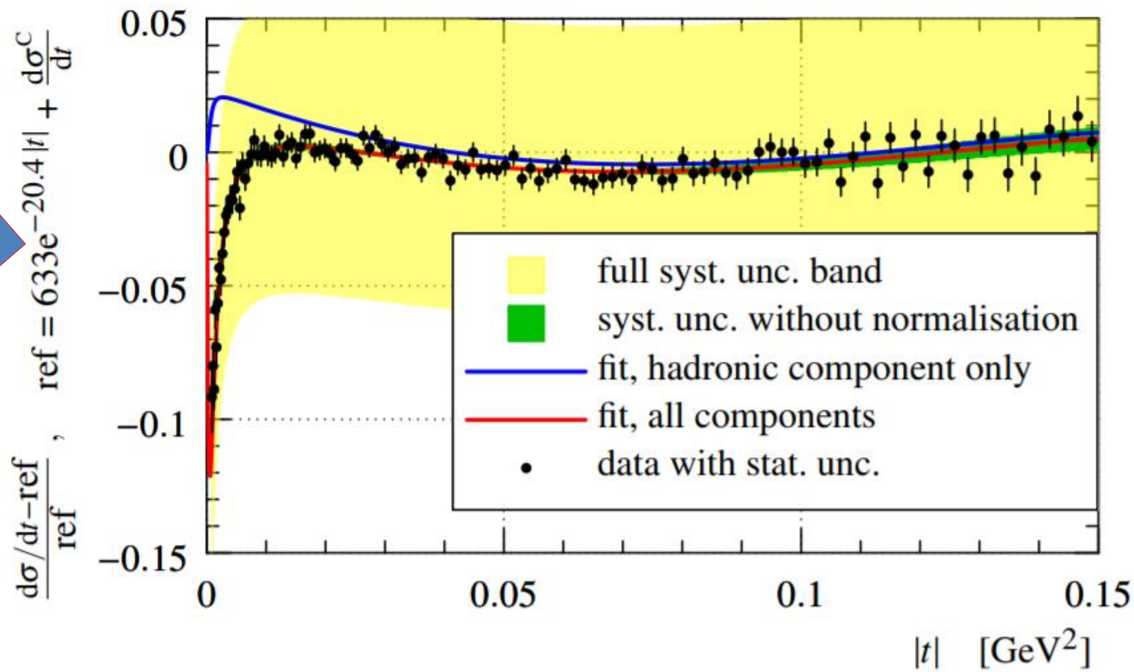


- **The ρ parameter:**

$$\rho = \left.\frac{\mathrm{Re}\,A^H}{\mathrm{Im}\,A^H}\right|_{t=0}$$

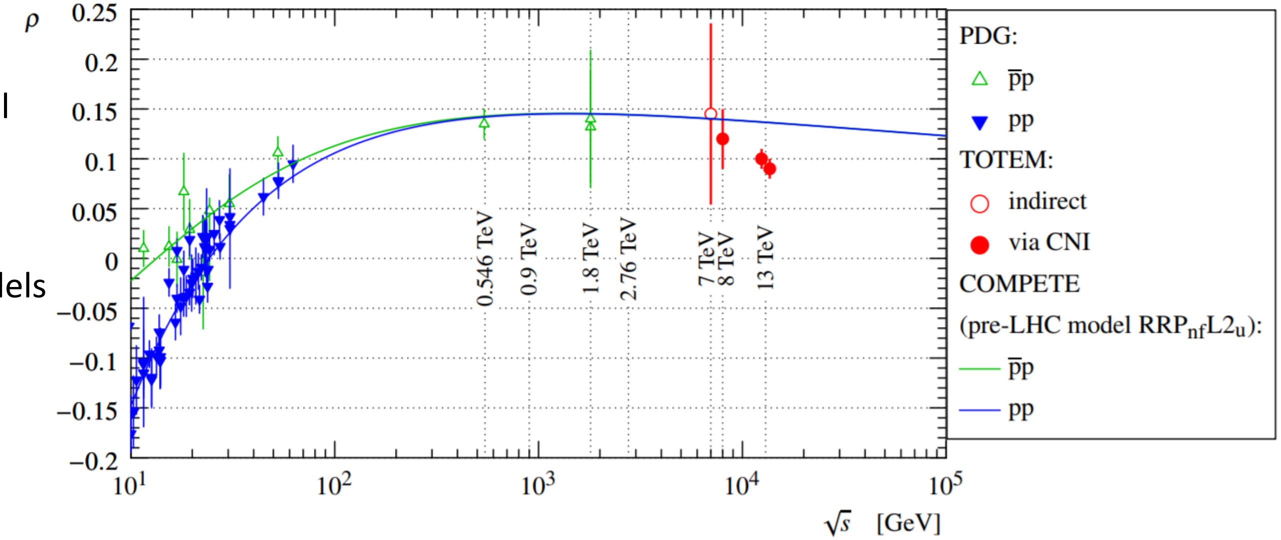
Interference in details and ρ measurements

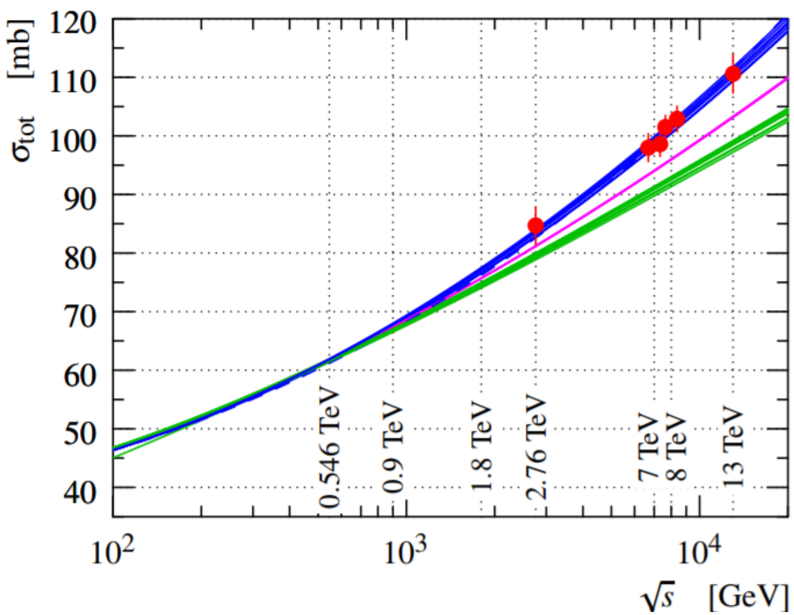
N_b	$\lvert t\rvert_{max} = 0.07\,\mathrm{GeV}^2$ χ^2/ndf	ρ	$\lvert t\rvert_{max} = 0.15\,\mathrm{GeV}^2$ χ^2/ndf	ρ
$\boxed{1}$	0.7	0.09 ± 0.01	2.6	-
2	0.6	0.10 ± 0.01	1.0	0.09 ± 0.01
$\boxed{3}$	0.6	0.09 ± 0.01	0.9	0.10 ± 0.01

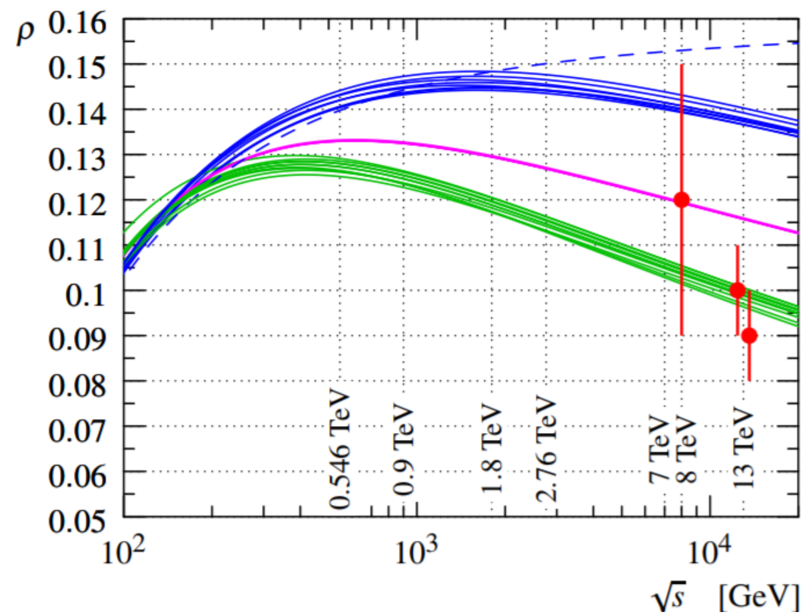


Overview of the ρ parameter evolution with energy

- Not compatible with conventional (COMPETE) models (that doesn't include exchange of a colourless 3-gluon bound state)
- Compatibility with improved models where t-channel exchange of a colourless 3-gluon bound state $1^{PC} = 1^{--}$ is added







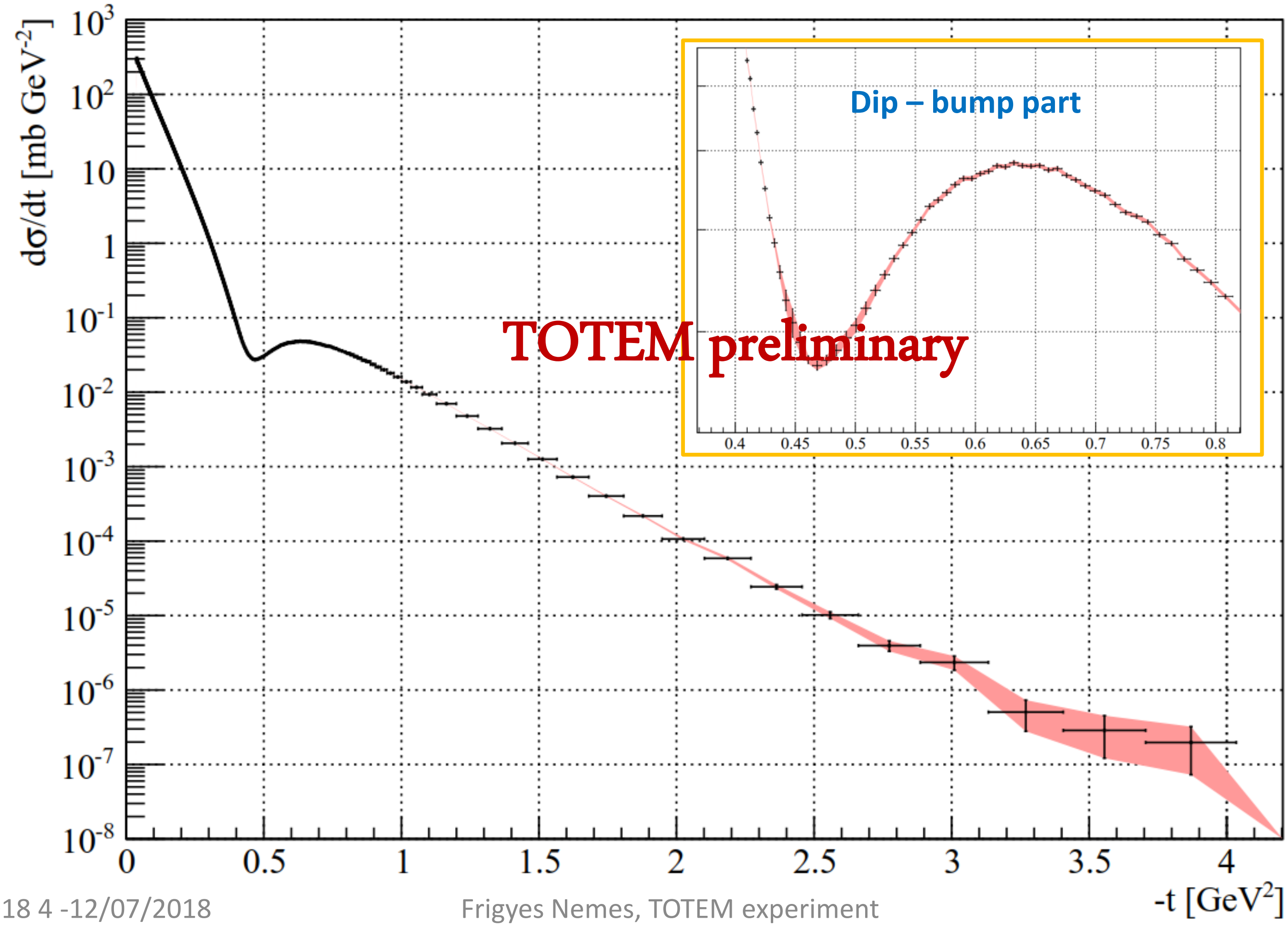
TOTEM differential cross-section measurement at $\sqrt{s}$ = 13 TeV

β^* = 90 m, 10σ_{RP} RP distance

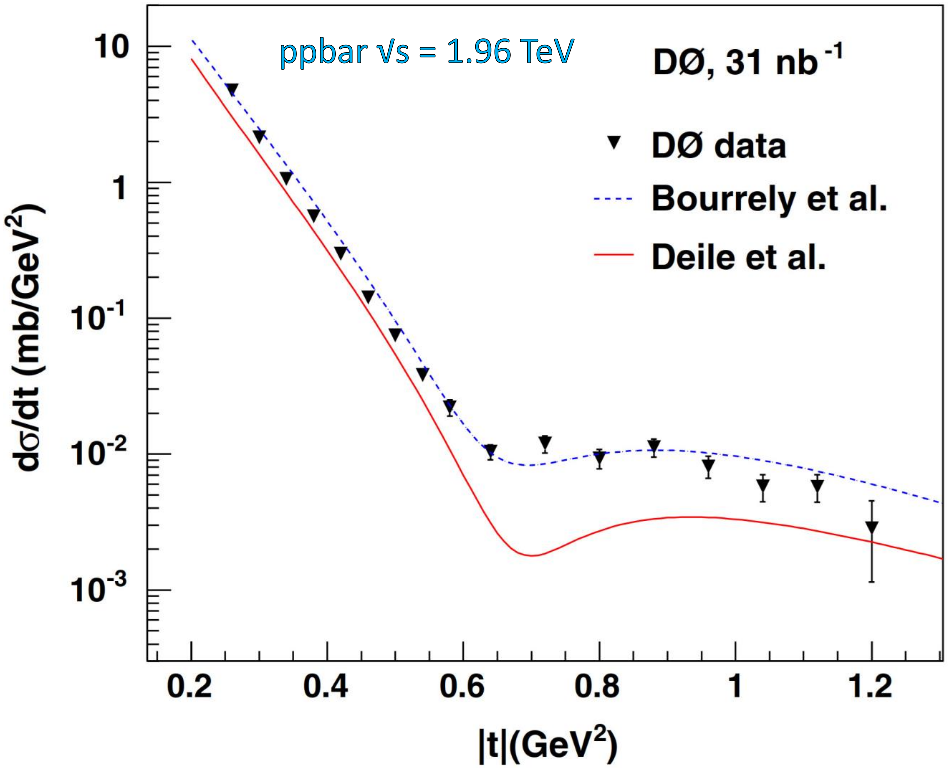
Differential cross-section (fully corrected)

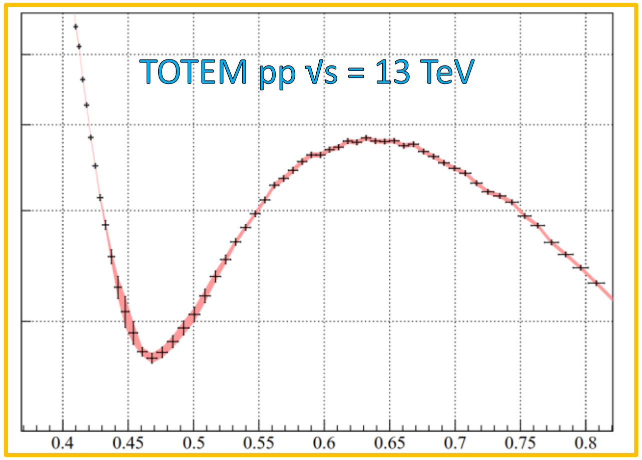
Note:

- O(10^9) observed elastic events (trigger rate **50 ×** Run I)
- Acceptance and beam divergence corrected
- 3/4 correction, matched optics
- Unfolded



The diffractive minimum in pp and ppbar collision

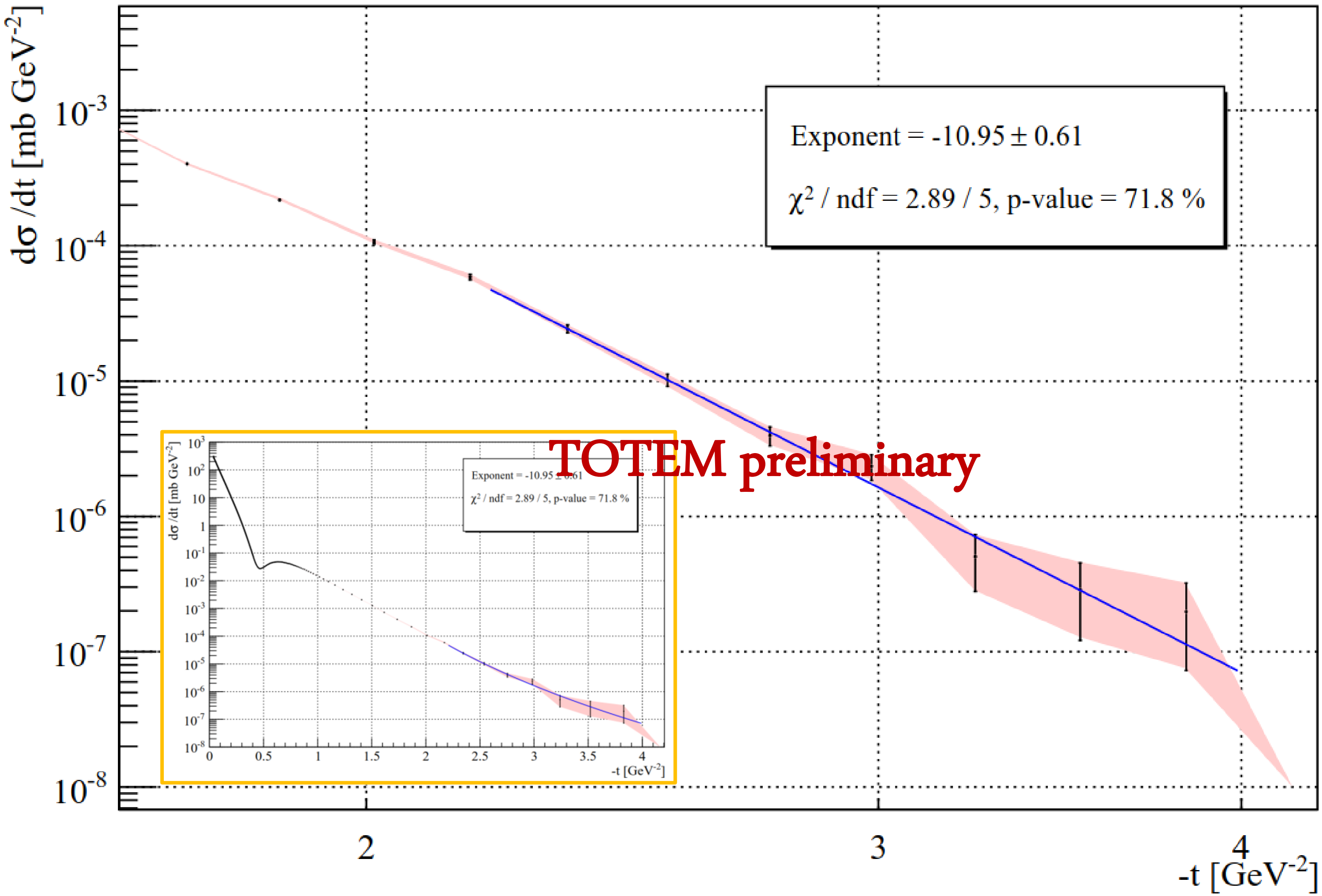




Note:

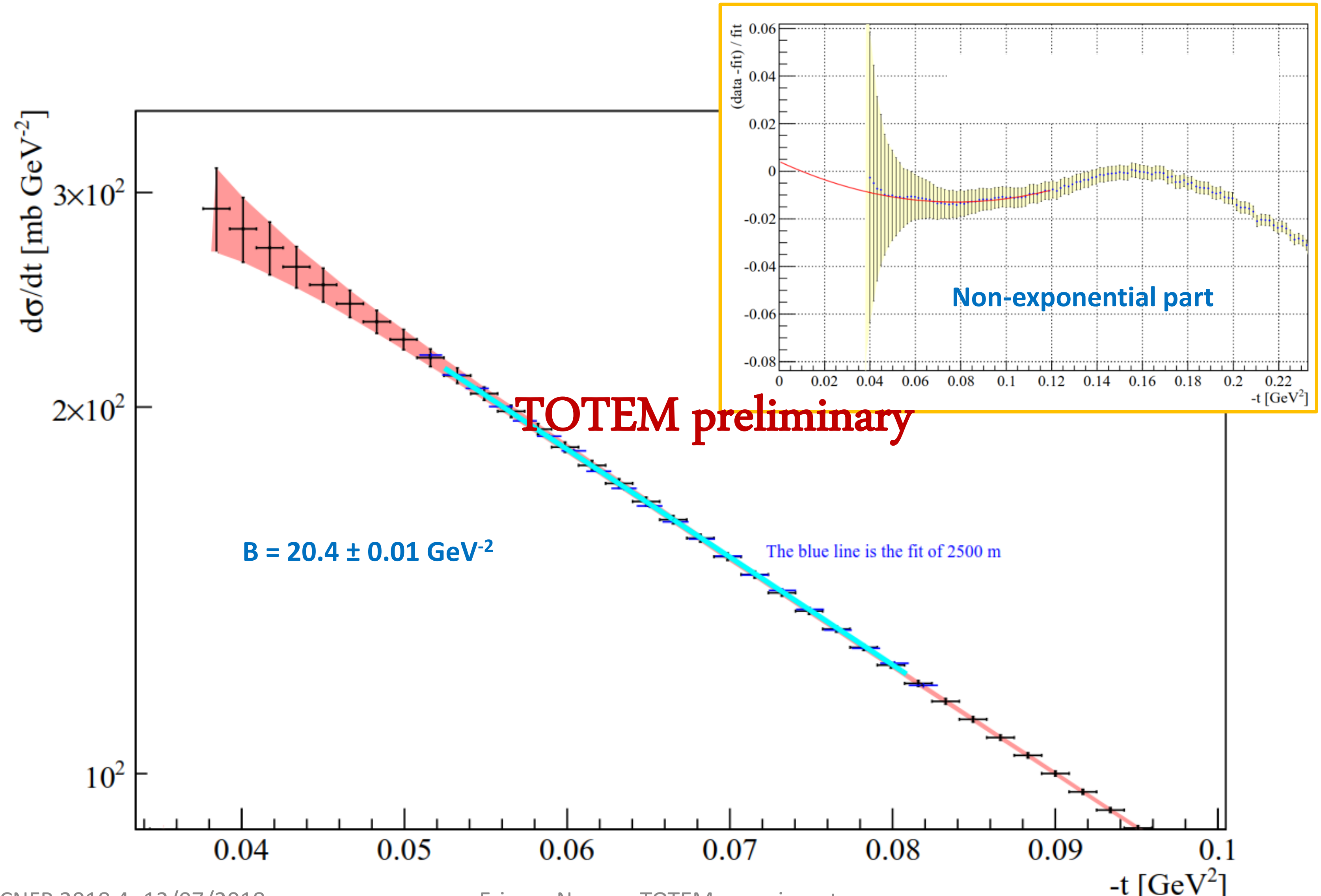
- Result confirms with unprecedented precision at the TeV scale the dip structure in elastic pp scattering (first observed at 7 TeV after the ISR) and brings to 5 sigma level the **incompatibility** at the diffractive dip between pp and ppbar, the latter measured by D0 still at the gluon-dominated TeV scale
- Not compatible with conventional (COMPETE) models (that doesn't include exchange of a colourless 3-gluon bound state)
- Compatibility with improved models where t-channel exchange of a colourless 3-gluon bound state $1^{PC} = 1^{--}$ is added

Large-t fit

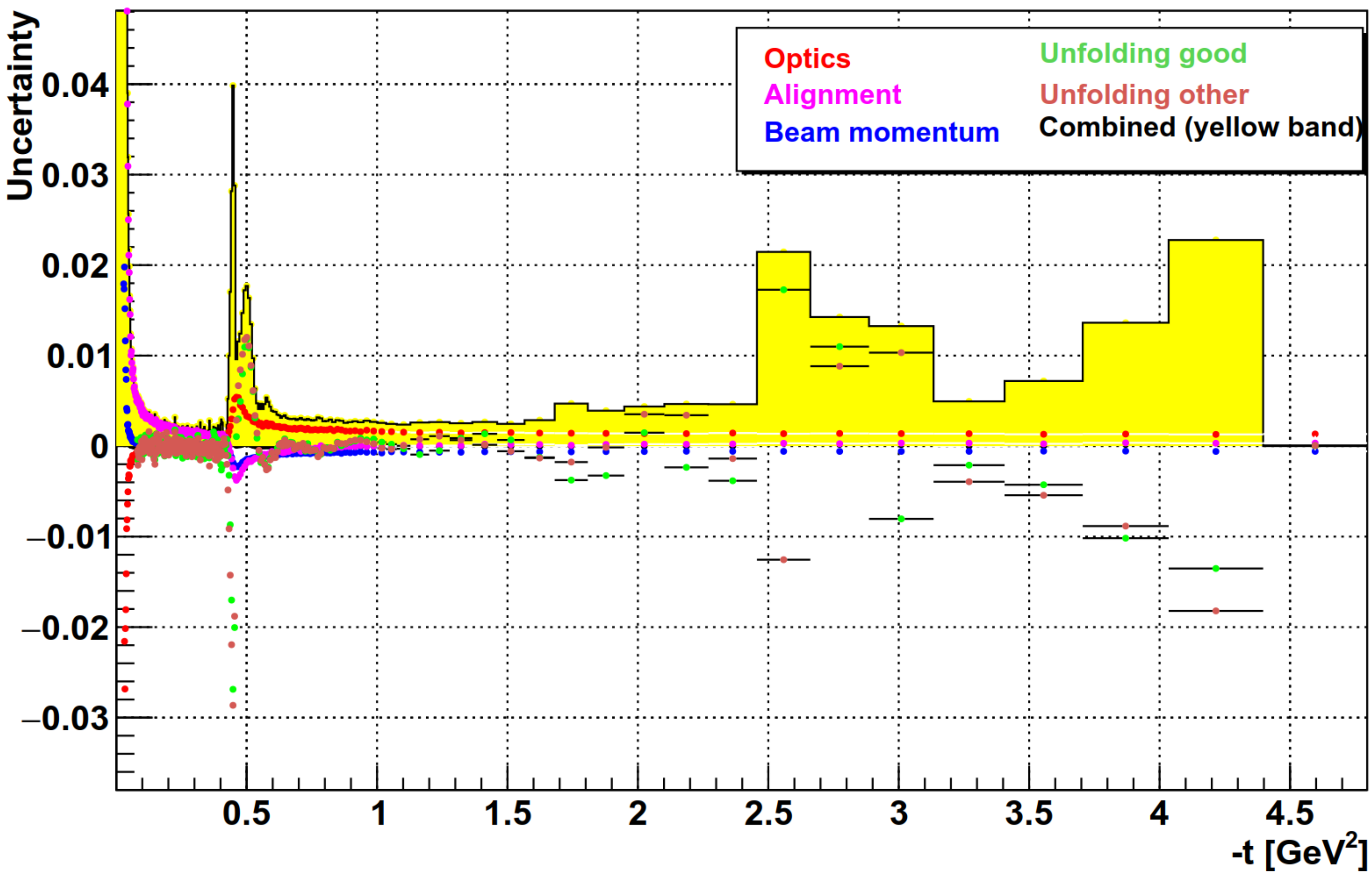


Exponent = -10.95 ± 0.61
χ2 / ndf = 2.89 / 5, p-value = 71.8 %
TOTEM preliminary
dσ /dt [mb GeV-2]
-t [GeV-2]

Low-t, normalization and non-exponential part



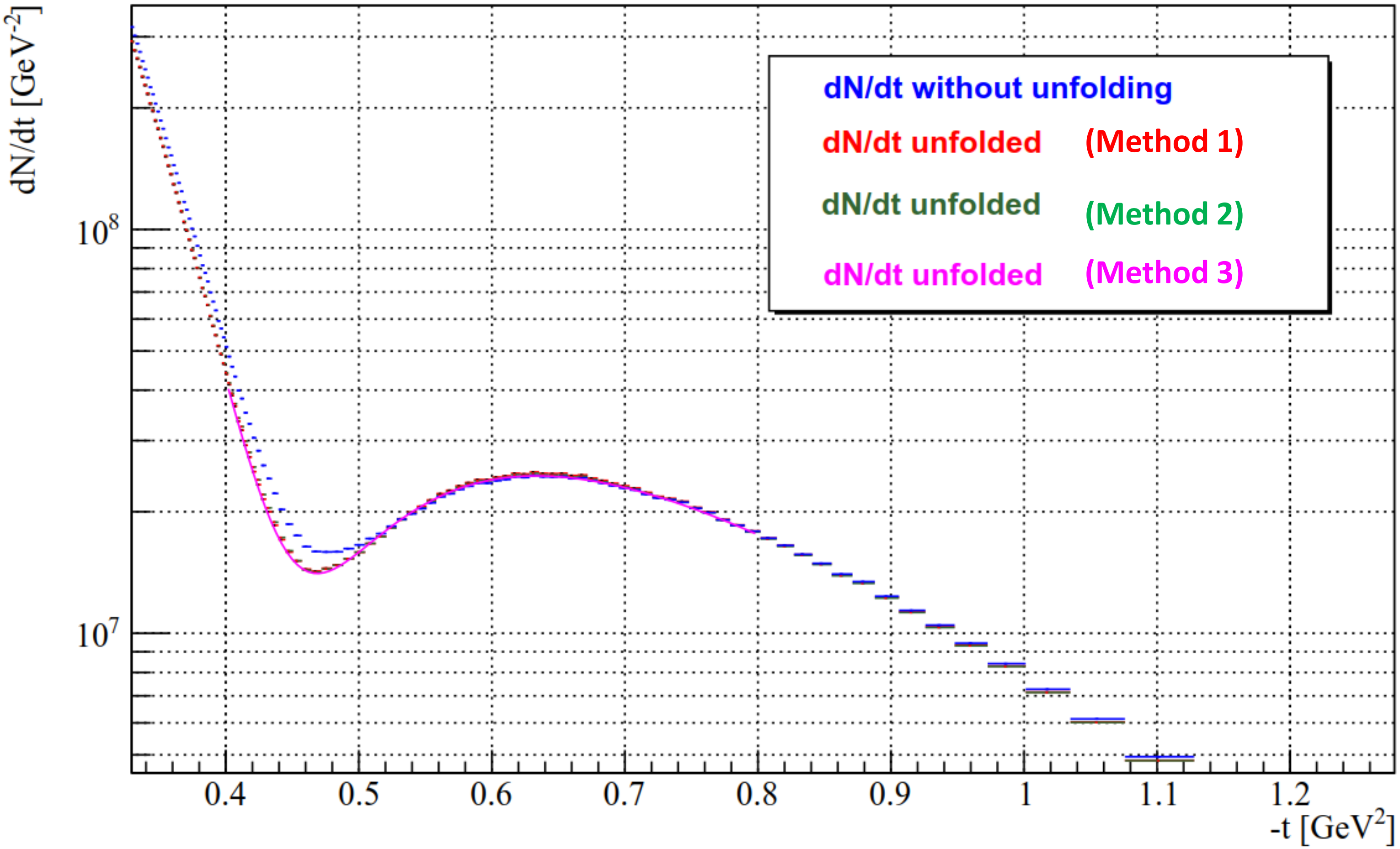
Systematic uncertainty summary



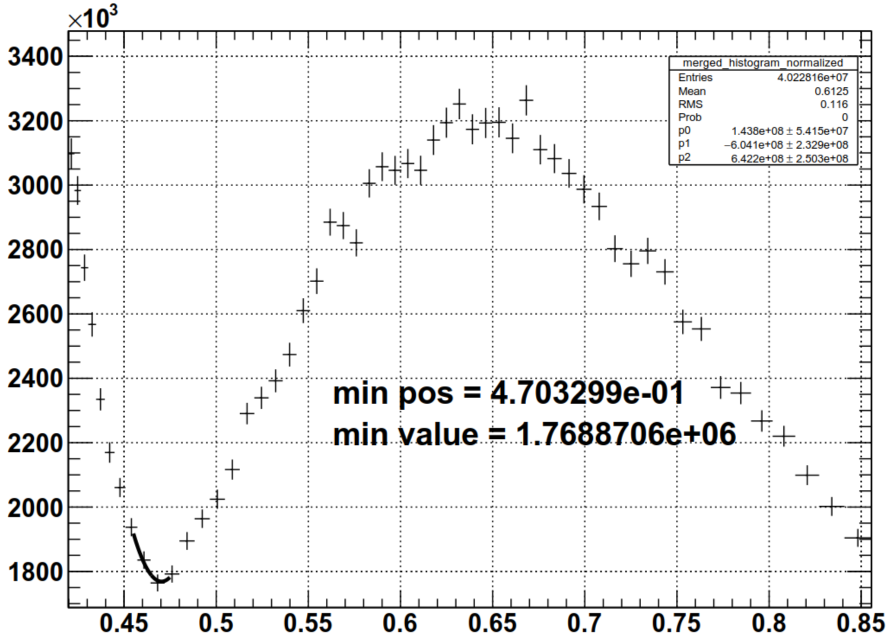
Unfolding of dN/dt: 3 different methods

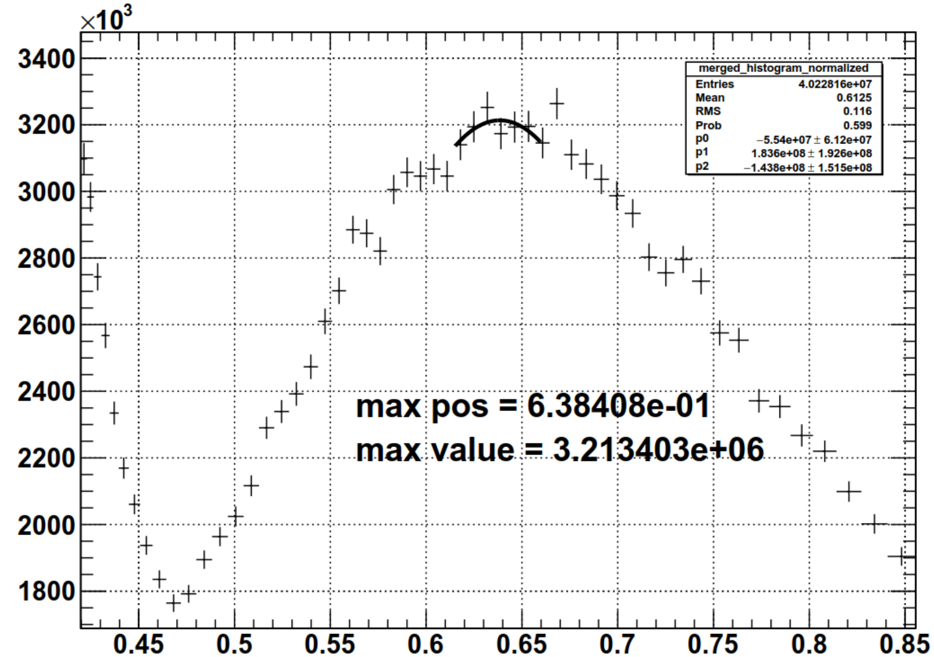
Note:

1. Bin-by-bin MC simulation of bin-migration
2. Inversion of the response matrix M
3. Gaussian deconvolution



Fit of dip and max





- The weighted average of all fills give dN/dt ratio between max / dip = 1.78 ± 0.05

Summary

- Results at $\sqrt{s}$ = 2.76 TeV
  - First total cross-section measurement
  - Change of $\sqrt{s}$ behavior of slope parameter B at around 3 TeV
- Results at $\sqrt{s}$ = 13 TeV
  - **First** total cross-section measurement (http://cds.cern.ch/record/2296409)
  - **First** ρ measurement (https://cds.cern.ch/record/2298154)
  - Conventional models (COMPETE) not able to describe simultaneously TOTEM σ_{tot} & ρ measurements
  - Data compatible with t-channel exchange of a colourless QCD 3 gluon $1^{PC} = 1^{--}$ bound state
  - High-statistics differential cross-section measurement at $\sqrt{s}$ = 13 TeV: confirming with unprecedented precision the dip structure in pp scattering at TeV scale: 5 σ level **incompatibility** of diffractive dip between pp and ppbar --> difference compatible with t-channel exchange of a colourless QCD 3 gluon $1^{PC} = 1^{--}$ bound state

Thank you for your attention !

Backup slides

Note on proton kinematics reconstruction & optics imperfections

Machine imperfections alter the optics:

- **Strength conversion error, $\sigma(B)/B \approx 10^{-3}$**
- **Beam momentum offset, $\sigma(p)/p \approx 10^{-3}$**
- Magnet rotations, $\sigma(\phi) \approx 1$ mrad
- Magnetic field harmonics, $\sigma(B)/B \approx 10^{-4}$
- Power converter errors, $\sigma(I)/I \approx 10^{-4}$
- Magnet positions Δx, $\Delta y \approx 100$ µm

$$t(v_x, L_x, L_y, \ldots, p) = -p^2 \cdot \left(\Theta_x^{*2} + \Theta_y^{*2}\right)$$

→ **Precise model of the LHC optics is indispensable!**

Novel method from TOTEM:

- Use **measured** proton data from RPs
- Based on kinematics of elastic candidates
- Published in New Journal of Physics
- http://iopscience.iop.org/1367-2630/16/10/103041/